Polar Meteorol. Glaciol., **13**, 43-52, 1999

THE RELATIONSHIP AMONG ACCUMULATION RATE, STABLE ISOTOPE RATIO AND SURFACE TEMPERATURE ON THE PLATEAU OF EAST DRONNING MAUD LAND, ANTARCTICA

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Abstract: During traverses in East Dronning Maud Land, which includes Dome Fuji Station (77°19′01″S, 39°42′12″E, elevation 3810 m a.s.l.), many glaciological observations have been conducted by the Japanese Antarctic Research Expedition. Among the quantities observed are annual net accumulation (A_{cc}: kg m^{-2}), stable oxygen isotope composition ($\delta^{18}O$: ‰) in the surface snow and mean annual surface temperature distribution. The characteristics of these quantities have been analyzed, and the following equation relating them was obtained:

$$A_{cc} = 1.104 \times 10^5 \exp\ (0.1462\ \delta^{18}O).$$

In addition, a relation between $\delta^{18}O$ and surface temperature has been obtained. These relations suggest a possibility that core chronology and surface temperature variations can be reproduced from the $\delta^{18}O$ values in the 2500 m-deep ice core drilled at Dome Fuji Station.

1. Introduction

The Japanese Antarctic Research Expedition (JARE) has drilled deep ice cores at Dome Fuji Station (77°19′01″S, 39°42′12″E, elevation 3810 m a.s.l.), and a 2500 m deep ice core has been obtained (DOME-F DEEP CORING GROUP, 1998). Estimation of the relationship between core depth and age is essential to reproduce the past environment through analysis of core samples.

The first estimation was carried out by AGETA *et al.* (1989) at Dome Camp (77°00′01″S, 35°00′00″E, elevation 3761 m a.s.l.). From research on tritium in a 5 m-deep surface pit, mean annual net accumulation of 3.2 cm (balance in water equivalent) from 1966 to 1985 was obtained. WATANABE *et al.* (1997) carried out the first core analysis on a 112.59 m-deep ice core obtained at Dome Fuji Station. From the results of analysis of ECM (Electric Conductivity Measurement) distribution along the core and field measurements of the core by JARE-36, the annual net accumulation (water equivalent) at Dome Fuji Station has been estimated to be between 2.5 cm and 3.0 cm.

Here we estimate the annual net accumulation using a different method than the previous studies mentioned above. Aiming at finding a method to determine the chronology of a deep core, we investigated the relationship among accumulation rate, stable oxygen isotope ratio in accumulated snow, and surface temperature, in East Dronning Maud Land.

2. Measurement of Annual Snow Depth

In East Dronning Maud Land, many oversnow traverses were carried out in the 1950's. On these, many snow stake measurements were conducted to measure the net amount of snow accumulation on the ice sheet. TAKAHASHI *et al.* (1994) summarize the surface mass balance in this region, from 69° S to 77° 30′S and from 20° W to 50° W.

In this paper, the results of snow stake measurements along oversnow traverse routes (Fig. 1), which lie in the Shirase Drainage, are summarized in Fig. 2. Along

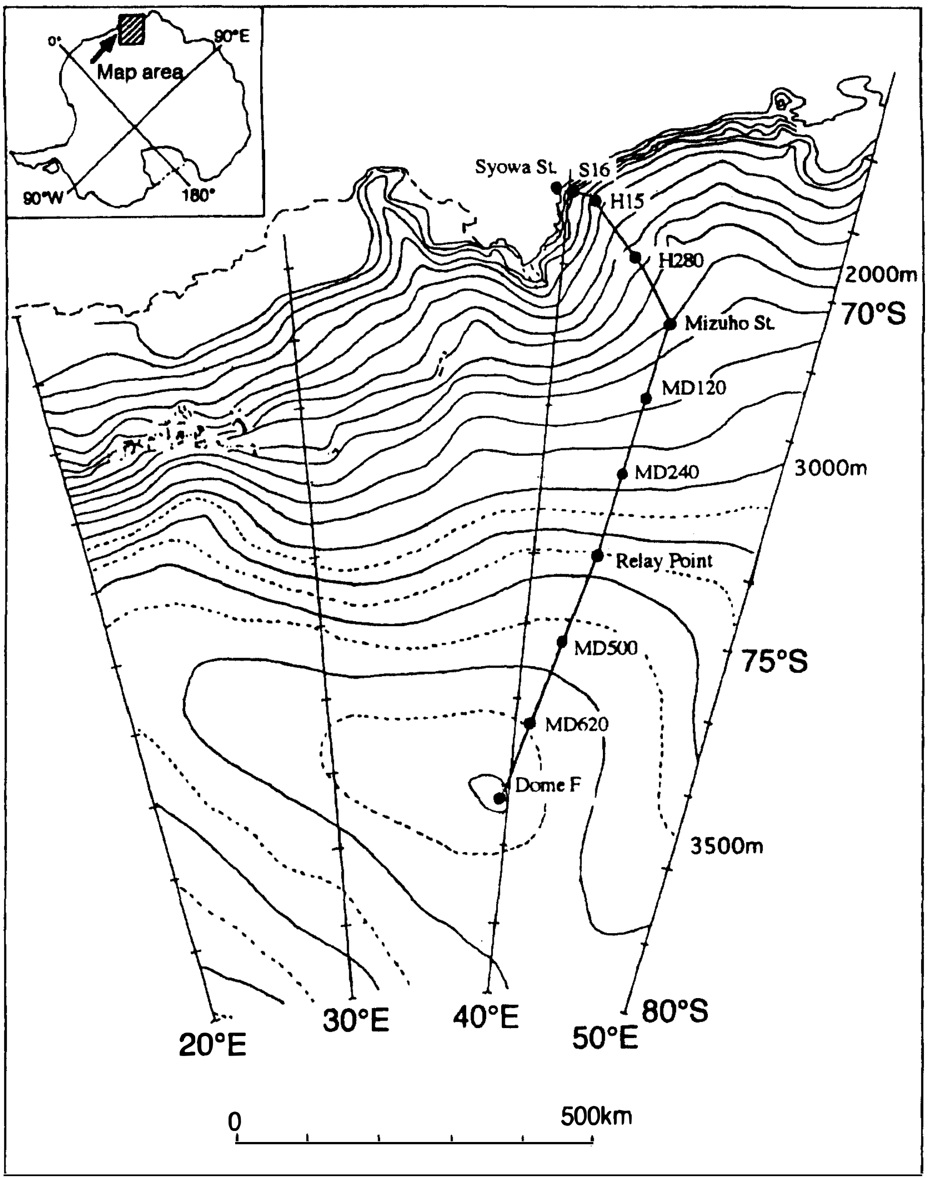

Fig. 1. Location map of traverse routes with snow stakes from S16 to Dome Fuji Station.

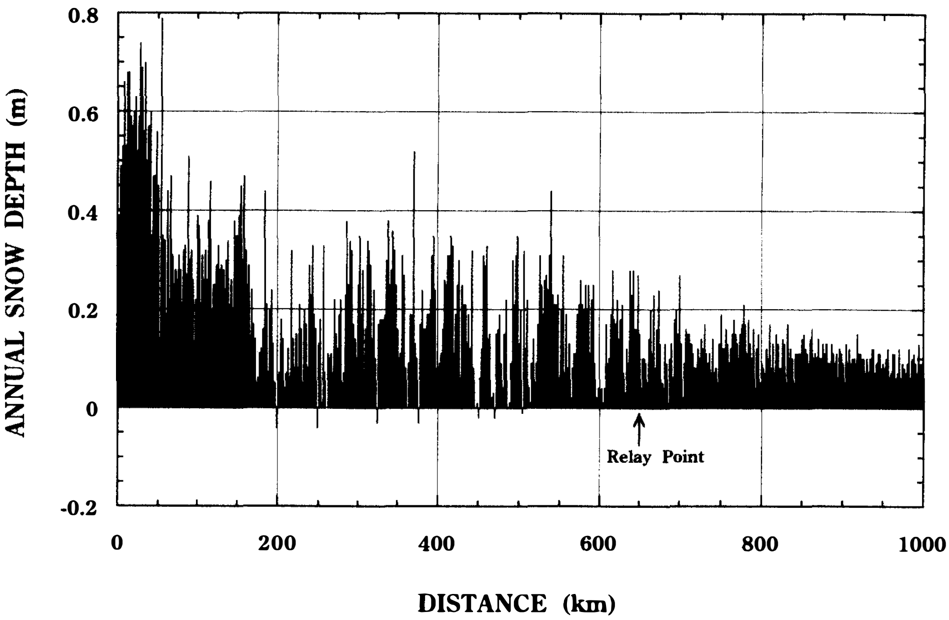

Fig. 2. Average annual snow depth for 5 years (1992–1996) from S16 to Relay Point and for 3 years (1994–1996) from Relay Point to Dome Fuji Station, observed by the snow stake method. Distances are measured from S16 along S-H-Z-MD routes.

these routes to Dome Fuji Station, which lies 1000 km inland, measurements for 503 snow stakes were conducted every year from 1992 to 1997 (KAMIYAMA *et al.*, 1994; MOTOYAMA *et al.*, 1995, 1999; SHIRAIWA *et al.*, 1996; AZUMA *et al.*, 1997). Snow stake measurements were carried out several times every year at 2 km intervals from S16 on the coast along routes S and H to Mizuho Station and from Mizuho Station along route MD to Dome Fuji Station. Average annual snow depths have been determined for 5 years, from January 1992 to January 1997, from S16 to the Relay Point, and for 3 years, from January 1994 to January 1997, from the Relay Point to Dome Fuji Station.

The average annual snow depth vs. distance from S16 is shown in Fig. 2. The annual snow depth decreases from 0.6 m at the coast to about 0.1 m inland, with some fluctuation in the intermediate region. Between 180 km and 240 km from the coast, the strong katabatic wind zone, and in the region of the glazed surface farther inland, the annual snow depths are extremely small. However, these fluctuations in annual snow depth petered out after about 600 km from the coast. FURUKAWA *et al.* (1996) reported snow surface features along this route in detail.

3. Distribution of Surface Snow Density

The accumulated surface mass per unit area is obtained by multiplying the accumulated snow depth by the density. Density was not measured at the time of every snow stake measurement, but only less frequently. Surface densities of accumulated snow measured during oversnow traverses in Dronning Maud Land, eastern Antarctica, from 1968 to 1997 have been reported by FUJIWARA and ENDO (1971), NARUSE (1975),

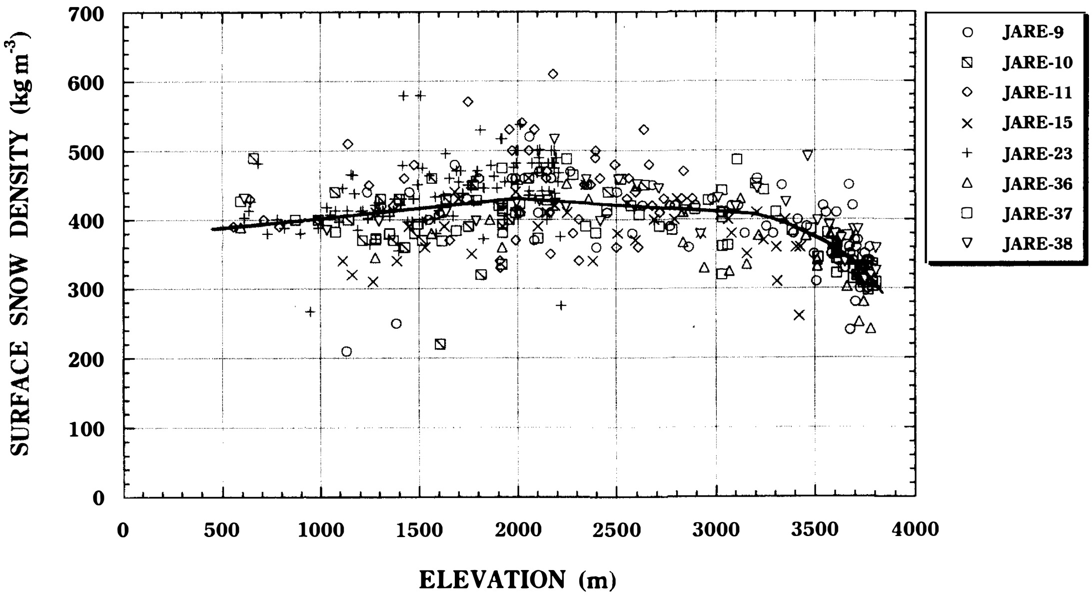

Fig. 3. Surface snow density versus elevation in east Dronning Maud Land. The solid line shows the simplified relation used to estimate surface annual net accumulation from annual snow depth and elevation. Snow densities are shown by various marks by different JARE parties (FUJIWARA and ENDO, 1971; NAURSE, 1975; WATANABE, 1975; SATOW, 1977; OHMAE, 1984; AZUMA et al., 1997; MOTOYAMA, 1999).

WATANABE (1975), SATOW (1977), OHMAE (1984), AZUMA *et al.* (1997) and MOTOYAMA *et al.* (1999). These are summarized as a function of elevation above sea level in Fig. 3. The densities given here are average values from the surface to 10 cm or 20 cm snow depth.

The features of the distribution suggest that there are 3 distinct regions, from 500 m to 2000 m, from 2000 m to 3000 m, and from 3000 m to 3800 m above sea level respectively. In the region from 500 m to 2000 m, density increases very slightly with elevation; from 2000 m to 3000 m, it decreases slightly; and from 3000 m to 3800 m it decreases more rapidly with increasing elevation.

These regions correspond to those reported by SHIMIZU *et al.* (1978) in glaciological and meteorological features. To give some examples, glazed surfaces with thermal cracks and high sastrugi are distributed widely in the region from 2000 m to 3000 m. Below 2000 m, a fine grain compact snow structure is well developed, while above 2000 m depth hoar is well developed. The surface Ram hardness fluctuates in the region from 2000 m to 3000 m. The ice sheet surface slope changes at 1000 m and 3000 m. Regarding the katabatic wind, from 1000 m to 3000 m is a stationary katabatic wind area; while above 3000 m is a weak katabatic wind area. The effect of cyclonic disturbances decreases above 3000 m (WATANABE, 1978).

FURUKAWA *et al.* (1996) also divided the study route into three regions based on the regional characteristics of snow surface features: coastal region, katabatic wind region and inland plateau region. These three regions roughly correspond to the regions mentioned above.

In the region from 500 m to 2000 m in elevation, the density of accumulated snow at snow stake measurement points is given by a linear regression equation:

$$\rho_{500\text{-}2000}=0.03135E+371.4 \qquad (R^2=0.046),$$

where ρ is surface snow density (kg m^{-3}) and E is elevation (m). The relation is also linear in the region from 2000 m to 3000 m:

$$\rho_{2000\text{-}3000}=-0.0330E+500.0 \qquad (R^2=-0.016).$$

In the region from 3000 m to 3800 m the regression equation becomes:

$$\rho_{3000\text{-}3800}=-1.952\times10^{-4}E^2+1.221E-1506 \qquad (R^2=0.420).$$

Using these regression equations, the density of accumulated snow at the elevation of any snow stake measurement point can be found. This can be then multiplied by the accumulated annual snow depth to determine the annual net accumulation (annual mass balance).

4. Distribution of Annual Net Accumulation

The annual net accumulation (annual mass balance) at each point found as described above averaged over 20 km (10 measurement points) is shown vs. elevation above sea level in Fig. 4. With elevation increases above 700 m, where the annual net accumulation is 250 kg m^{-2}, the annual net accumulation gradually decreases to about 25 kg m^{-2}. The bars in the figure show the standard deviation of annual net accumulation at 20 km intervals. These vary between 30 kg m^{-2} to 70 kg m^{-2} in the area from 700 m to 3000 m in elevation, but above 3000 m the standard deviation gradually

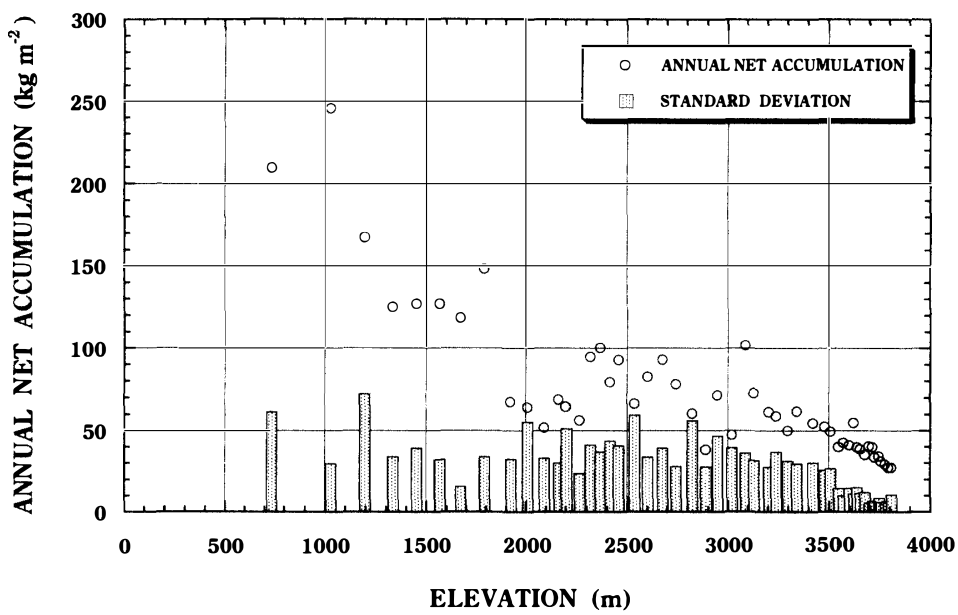

Fig. 4. Annual net accumulation versus elevation along S-H-Z-MD routes. Circles are mean accumulation rates every 20 km (10 stake sites). Each bar graph shows the standard deviation of the ten values.

decreases, with the decrease in annual net accumulation.

5. The Relation between Stable Oxygen Isotope Ratio ($\delta^{18}O$) and Elevation

SATOW and WATANABE (1992) clarified the distribution characteristics of the stable oxygen isotope ratio ($\delta^{18}O$) in the surface snow in this region. Adding new data, we found the following equation relating $\delta^{18}O$ (‰) to elevation above sea level (E, in meters) (Fig. 5):

$$\delta^{18}O = -0.01188E - 11.04 \qquad (R^2 = 0.979). \qquad (1)$$

The $\delta^{18}O$ values are average ones obtained from analyzing the 2 m pit and the 10 m-depth core; 3 points on the coast, marked by open circles: Roi Baudouin Station (GONFIANTINI *et al.*, 1963), Syowa Station and Molodezhnaya Station (GORDIYENKO *et al.*, 1976), are

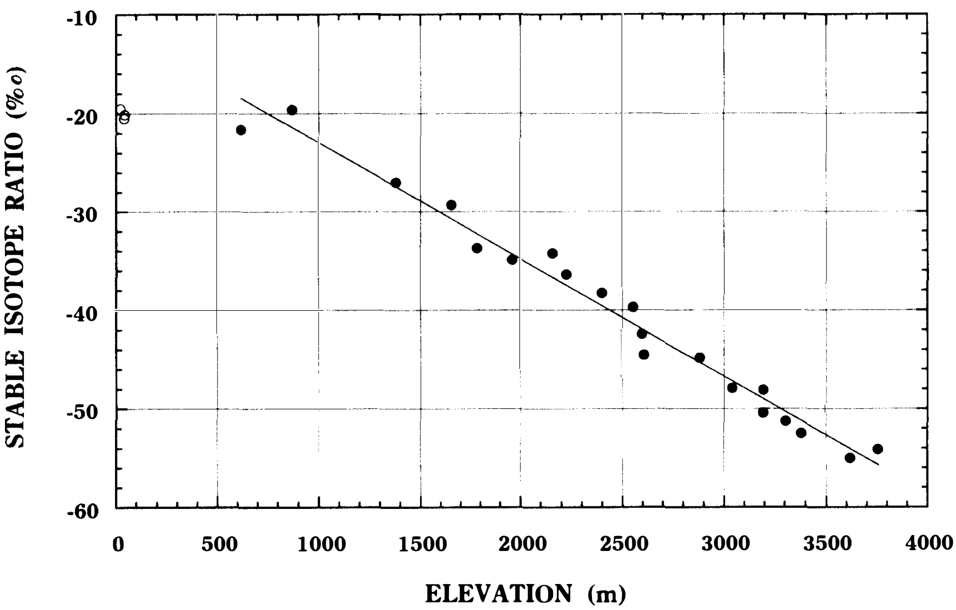

Fig. 5. Mean near-surface $\delta^{18}O$ values of snow plotted against elevation. The straight line shows the eq. (1).

excluded from the regression equation.

6. The Relationship among Annual Net Accumulation, Stable Oxygen Isotope Ratio ($\delta^{18}O$) and Surface Temperature on the Plateau near Dome Fuji Station

At points at which the annual net accumulation was measured, eq. (1) was used to find values of $\delta^{18}O$ at each elevation. Then the relationship between the $\delta^{18}O$ value and the annual net accumulation was derived. This relationship below −51‰ in the weak katabatic wind area is shown in Fig. 6, since the $\delta^{18}O$ value for the Dome Fuji deep core is in the range from −51‰ to −60‰. Black circles show mean annual net accumulation *vs.* $\delta^{18}O$ values at 20 km intervals. The open circle shows Dome Camp, which is

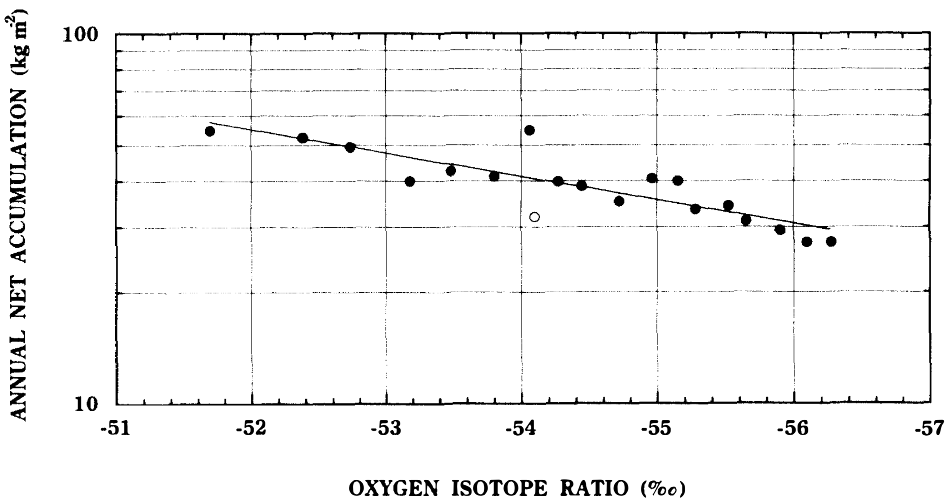

Fig. 6. Annual net accumulation versus stable isotope ratio ($\delta^{18}O$) below -51‰ on the plateau. Black circles are mean annual net accumulation every 20 km. The open circle shows the value at Dome Camp (AGETA et al., 1989, 1991). The line shows the eq. (2).

near Dome Fuji Station, where the annual net accumulation was determined by analysis of samples from 5 m pits and the average δ^{18}O values of accumulated snow at 5 m depth below the surface (AGETA *et al.*, 1989, 1991). A regression curve was obtained, leading to the following equation:

$$A_{cc}=1.104\times10^5 \exp\,(0.1462\,\delta^{18}\mathrm{O}) \qquad (R^2=0.751), \tag{2}$$

where A_{cc} is annual net accumulation (kg m^{-2}).

This equation shows the relationship between δ^{18}O values and annual net accumulation in the region above 3300 m elevation. If it is assumed that this relationship also applied in accumulated snow in the past, then this eq. (2) can be applied to the δ^{18}O values in deep cores to calculate the annual net accumulation in the past at that point. Such integrated values can be used to determine the ages of ice layers in the core.

SATOW and WATANABE (1992) analyzed the relationship between the stable oxygen isotope ratio and the 10 m snow temperature (T in °C, close to mean annual surface temperature) in this whole region. So adding further new data, we obtained the following equation (Fig. 7):

$$\delta^{18}\mathrm{O}=0.852T-7.92 \qquad (R^2=0.978). \tag{3}$$

The following equation is obtained from eq. (3).

$$T=1.17\,\delta^{18}\mathrm{O}+9.30. \tag{4}$$

In the region above 3000 m in elevation, we have:

$$\delta^{18}\mathrm{O}=0.557T-22.8 \qquad (R^2=0.970), \tag{5}$$

and

$$T=1.80\,\delta^{18}\mathrm{O}+40.9. \tag{6}$$

Using eq. (6), we can estimate mean surface temperature in the past from the δ^{18}O value

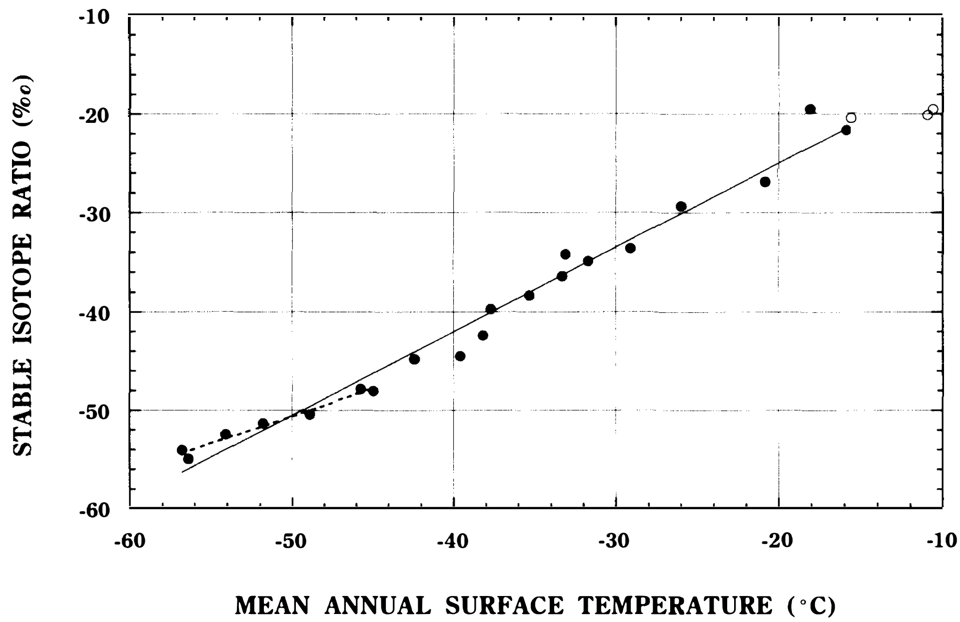

Fig. 7. Mean near-surface $\delta^{18}O$ values of snow plotted against mean annual surface temperature (10 m snow temperature). The regression line is calculated except for 3 points (open circles) on the coast. The straight line is based on eq. (3) and the dotted line is based on eq. (5).

in a deep core drilled at Dome Fuji Station.

7. Conclusions

Snow accumulation rates along a route from the coast to Dome Fuji Station were obtained by using the compiled data of annual snow depth and surface snow density on East Dronning Maud Land measured by the Japanese Antarctic Research Expeditions. There exists a certain relation between the annual net accumulation distribution and the $\delta^{18}O$ distribution of surface snow. By using this relation and a steady state ice flow model: *e.g.* a simple Dansgaard-Johnsen model (DANSGAARD and JOHNSEN, 1969), we will estimate the annual net accumulation in the past and determine the dating of the Dome Fuji ice core. Then the relation between mean surface temperature and mean $\delta^{18}O$ of surface snow enables one to estimate palaeotemperature variations from the $\delta^{18}O$ distribution record of Dome Fuji ice core (WATANABE *et al.*, 1999).

Acknowledgments

We thank the following colleagues of the glaciological program in Japanese Antarctic Research Expedition: Y. AGETA, Y. FUJII, K. KAMIYAMA and S. TAKAHASHI for advice and discussion. This work was supported by a Grand-in-Aid for Science Research (No. 10204101) from Ministry of Education, Science, Sports and Culture, Japanese Government.

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(Received May 1, 1999; Revised manuscript accepted September 22, 1999)